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AN ANALYSIS OF EXPERIMENTAL DATA ON ENTRANCE EFFECTS IN CIRCULAR THRUST BEARINGS

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by

S. P. Carfagno

September 1966

Prepared under

Contract Nonr-2342 (00)
Task NR 062-316

Supported Jointly by

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ATOMIC ENERGY COMMISSION
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Administered by

OFFICE OF NAVAL RESEARCH
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THE FRANKLIN INSTITUTE RESEARCH LABORATORIES

BENJAMIN FRANKLIN PARKWAY AT 20TH STREET, PHILA. 3, PA.

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ABSTRACT

An empirical method is presented for taking entrance effects into account in computing flow rates and load-carrying capacities of circular thrust bearings. Because of the limited data on which it is based, the method is applicable only to bearings having an 0.020-in. diameter supply hole; but it can be generalized when data for other supply hole diameters are obtained. When applied to the geometry for which experimental data were available, the procedure yielded values of flow rate and load falling within approximately 10 per cent of the experimental values.

NOMENCLATURE

a	Velocity of sound.
d_b	Outer diameter of bearing ($2\ r_b$).
d_o	Diameter of bearing gas supply hole ($2\ r_o$).
h	Bearing clearance.
m	Mass rate of gas flow.
p	Gas pressure.
r	Radial coordinate.
r_b	Outer radius of bearing.
r_o	Radius of bearing gas supply hole.
$\Re$	Universal gas constant (2.55×10^5 in.^{2}/sec^2 deg F, for N_2).
T	Absolute temperature of gas (°R).
W	Load-carrying capacity of bearing.

GREEK SYMBOLS

γ	c_p/c_v
ρ	Density of gas.
μ	Viscosity of gas.

SUBSCRIPTS

a	Ambient conditions.
b	Refers to bearing.
c	Indicates "choked" flow.
C	Computed value.

NOMENCLATURE (CONT.)

n   Nominal value.

o   Supply conditions.

t   Theoretical value.

SUPERSCRIPTS

*   Conditions at throat.

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1. INTRODUCTION

A procedure is presented for taking entrance effects into account in computing flow rates and load-carrying capacities of circular thrust bearings.

The analysis is based on the data given in Ref. 1 for a 2.800-in. diameter* circular thrust bearing having an 0.020-in. diameter supply hole. The procedure to be described permits one to take entrance effects into account in the computation of load-carrying capacity and flow rate for a given choice of bearing diameter and clearance. Because of the limited data on which it is based, the method is applicable only to circular thrust bearings having an 0.020-in. diameter supply hole, but it can be generalized when experimental data for supply holes of other diameters become available. It is also possible to extend the scheme for application to bearings of other types.

While the present analysis is an improvement of one given in Ref. 1 (Section 7.2.5), it should be regarded as an interim result due to the limited data on which it is based.

* The diameter was given erroneously as 2.750 in. in Reference 1.

2. ANALYSIS

2.1 Experimental Basis

The first requirement in the development of the design scheme was to find a way of expressing the information contained by the experimental data in a useful non-dimensional form. After trying several variations, it was found convenient to display the load data by defining a radius, r_e, and a pressure, p_e, as shown in Figure 1. The significance of the definition of r_e and p_e is the following. The actual pressure profile is replaced by a completely laminar profile by extrapolating the laminar portion of the true profile to a radius r_e such that, excluding any contributions for $r<r_e$, the calculated load carrying capacity for the new pressure profile equals the value of load determined by experiment diminished by the contribution for $r<r_o$.* This procedure resulted in part from the observation that the true pressure profiles were laminar except in small areas near the edge of the supply hole.

A plot of r_e/r_o vs. p_o/p_e is given in Figure 2 for a 2.800-inch diameter thrust bearing having a square-edged supply hole of diameter 0.020 inch. The equation of the line drawn through the data points is

$$r_e/r_o = 1.2\ (p_o/p_e) - 0.2 \qquad (1)^{**}$$

Because of difficulties associated with Test 10, the validity of the data point contributed by it is in doubt; therefore it was disregarded in drawing the line. It may be noted that the available data were such that the slope of the line is determined mostly by the points for the largest clearance, 1.6 mil.

*See equation in caption of Figure 1 and the sample computation in Appendix A. The procedure has been applied only to square-edged supply holes; with slight modification it could be applied to other types of holes also.

**Note that the line was drawn so $r_e = r_o$ when $p_e = p_o$.

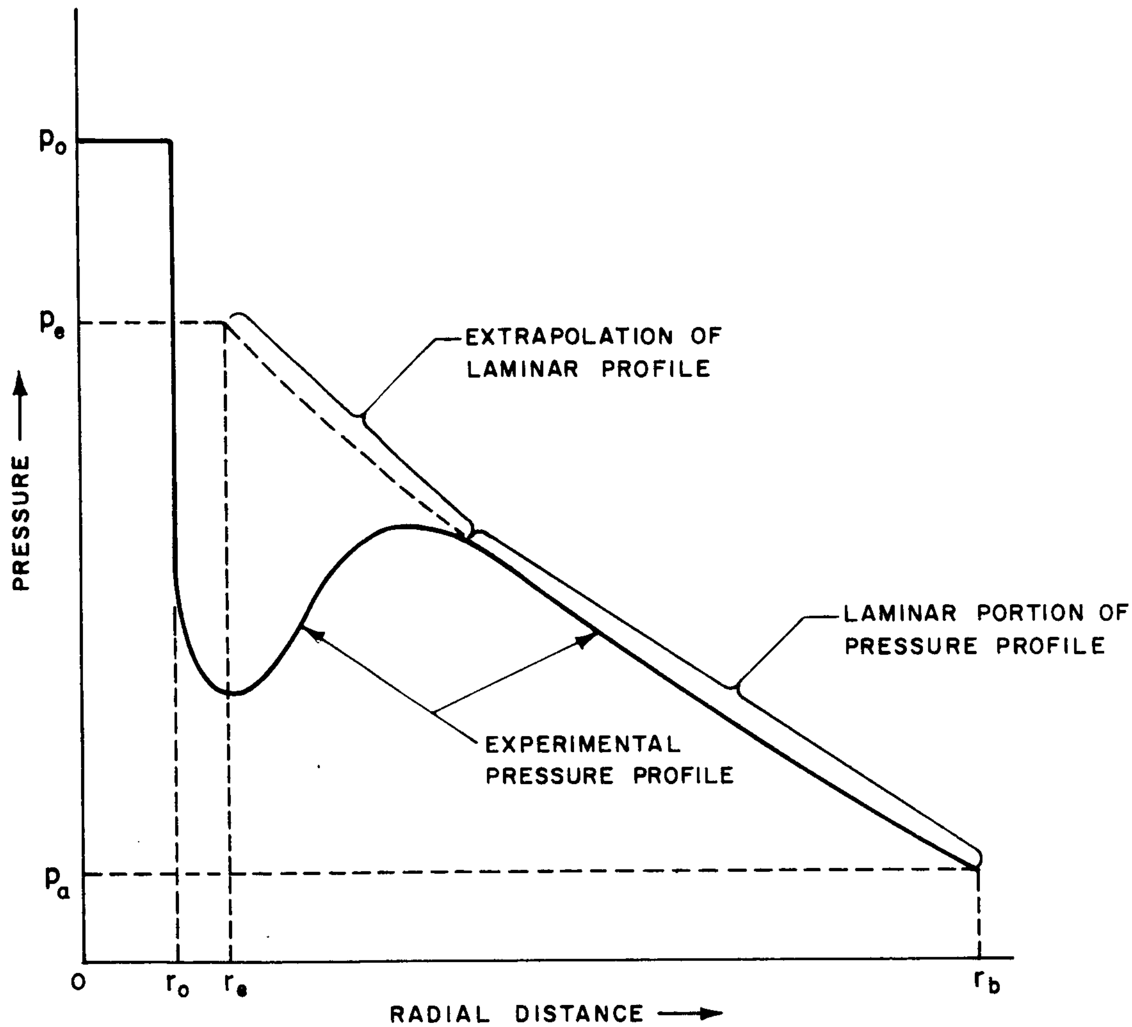

Fig. 1 - Definition of r_e and p_e.

Radius r_e was chosen so that:

$$\underbrace{\int_{r_e}^{r_b} 2\pi p r dr}_{\text{(Integrated along laminar profile)}} - \pi (r_b^2 - r_e^2) p_a = \underbrace{\text{Load}}_{\text{(Experimental Value)}} - \pi r_o^2 (p_o - p_a)$$

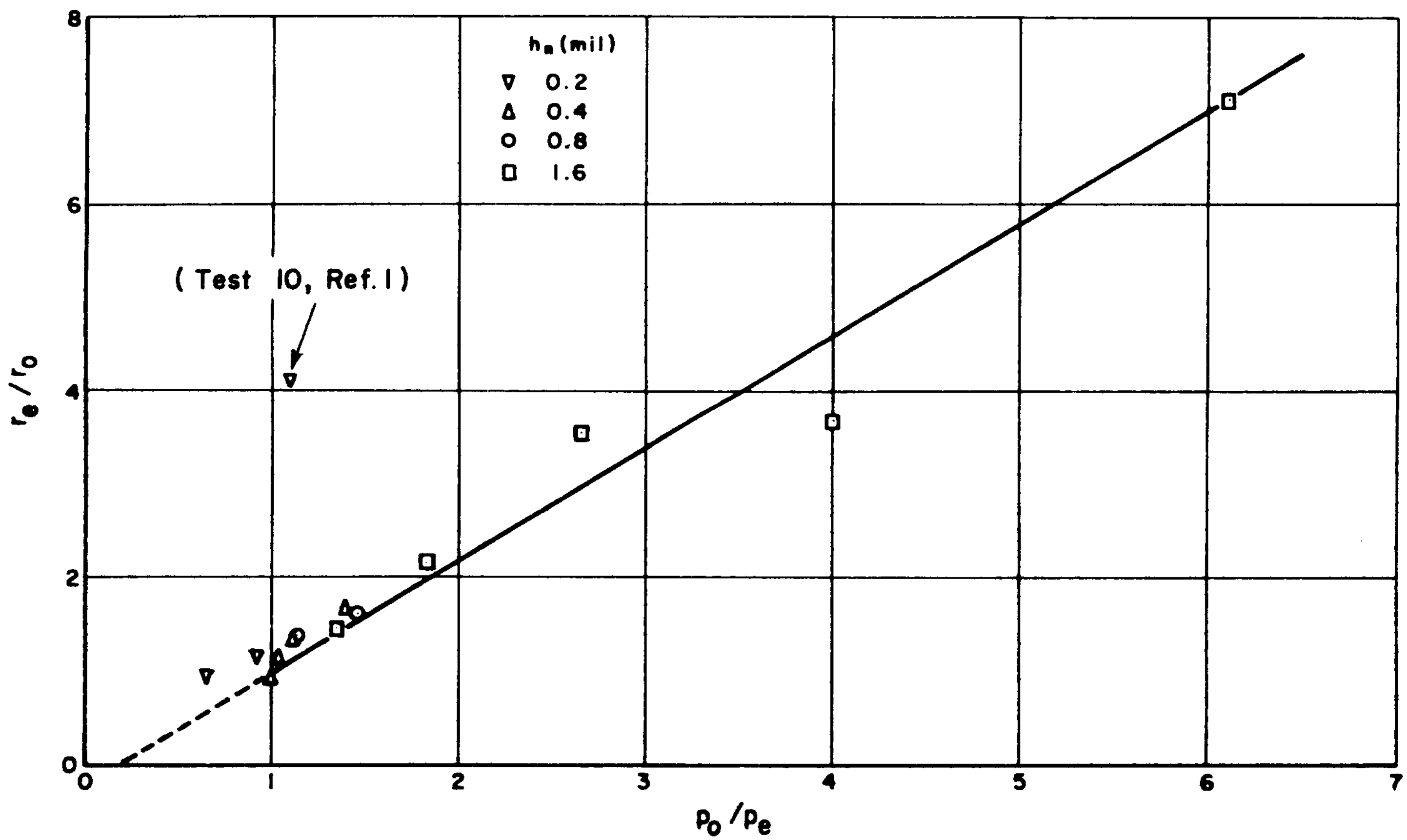

Fig. 2 - Graph of r_e/r_o vs. p_o/p_e for Circular Thrust Bearing With Square-Edged Supply Hole.

r_o = 0.010 in.
r_b = 1.400 in.

Our next step was to seek a general relation for the flow data. In Figure 3, the flow parameter m/m_c has been plotted as a function of p_e/p_o. Here m is the measured flow rate, and m_c is the computed flow rate for choked flow through the throat of the bearing.* A dashed curve has been drawn on the same graph for the isentropic flow relation.

$$\left.\begin{aligned} \left(m/m_c\right)_t &= \left(\frac{2}{\gamma+1}\right)^{-\frac{1}{(\gamma-1)}} \left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{1}{2}} \left\{\left(p_e/p_o\right)^{\frac{2}{\gamma}} \left[1 - \left(p_e/p_o\right)^{\frac{(\gamma-1)}{\gamma}}\right]\right\}^{\frac{1}{2}} \\ &\text{for } [2/(\gamma+1)]^{\gamma/(\gamma-1)} \le p_e/p_o \le 1, \\ \left(m/m_c\right)_t &= 1, \text{ for } o \le p_e/p_o \le [2/(\gamma+1)]^{\gamma/(\gamma-1)} . \end{aligned}\right\} \quad (2)$$

While there is substantial deviation between the experimental curves and the isentropic flow relation, it proved to be useful to accept Equation (2) as an approximately general relation for the experimental flow data. This means that we are imagining the hypothetical bearing, that has a completely laminar pressure profile, with $p = p_e$ at $r = r_e$, as being fed from a reservoir at pressure p_o, through a channel having a throat at its exit, where the pressure is p_e. The channel exit coincides with the entrance to the bearing film at $r = r_e$. This physical picture should be regarded only as an approximate way of representing the losses due to entrance effects.

2.2 Development of Equations

Having prepared the above ground, we can now outline the computation procedure. We will list the steps which are required and then develop the necessary equations. The steps are as follows:

*See Equation (4)

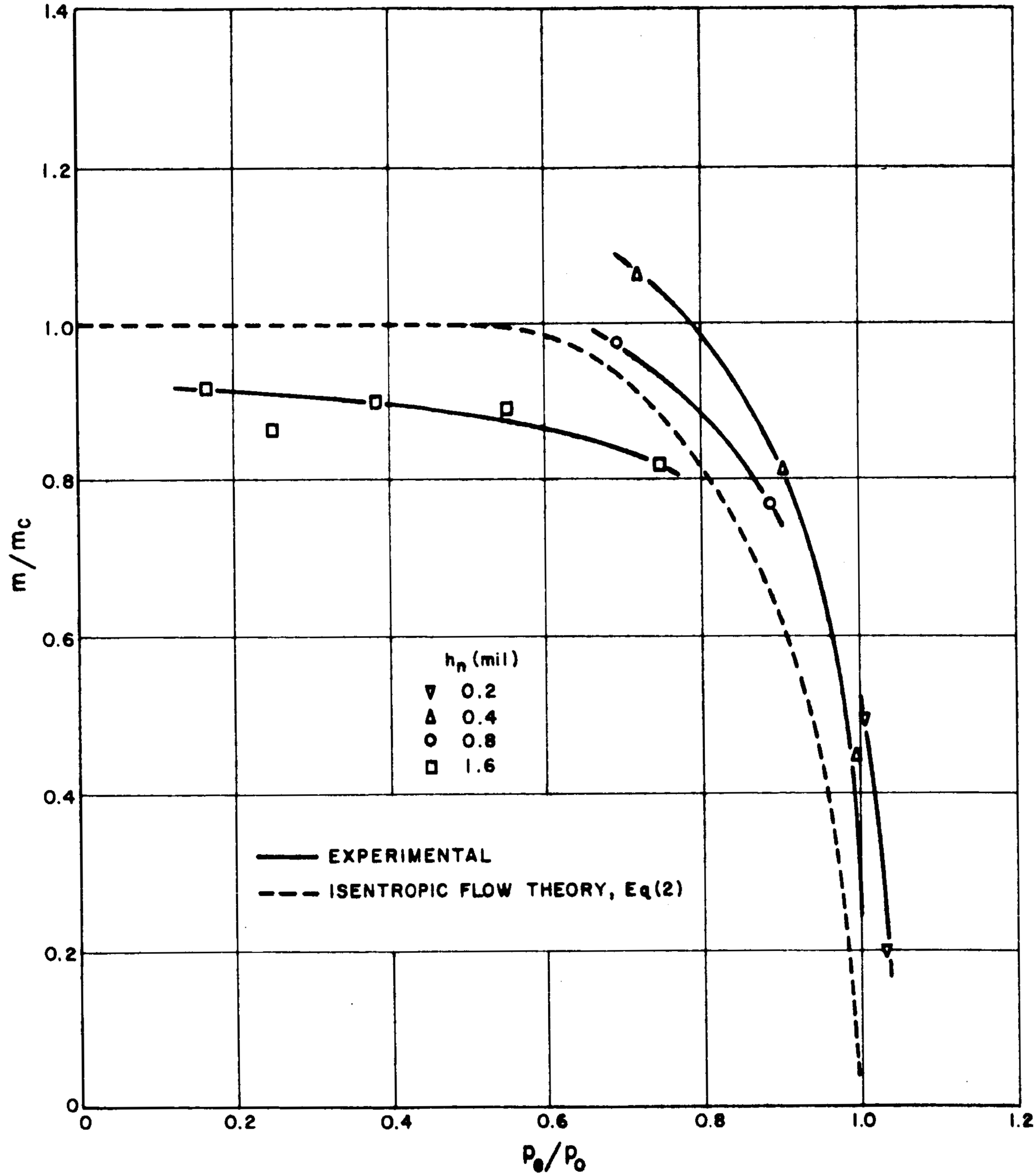

Fig. 3 - Graph of m/m_c vs. p_e/p_o for Circular Thrust Bearing With Square-Edged Supply Hole.

$r_o = 0.010$ in.

$r_b = 1.400$ in.

1. Determine the properties of the supply gas: γ, $\Re$, p_o, T_o. (The exit pressure and temperature, at $r = r_b$, were assumed to be p_a and T_a.)
2. Choose the bearing geometry: r_o, r_b, h. (Limitations on geometry are discussed below.)
3. Determine p_e/p_o by requiring that the flow rate, computed with the isentropic relation (Eq. 2), be equal to the theoretical flow rate through a circular thrust bearing having compressible, viscous, isothermal flow throughout the gas film. (This step requires the use of Eq. 1, as is shown below.)
4. Compute the load-carrying capacity for the laminar pressure profile (Figure 1).

The equations necessary to carry out the above steps are developed as follows:

For compressible, viscous, isothermal flow through a circular thrust bearing having a pressure p_e at the entrance to the gas film, $r = r_e$, the flow rate is given by

$$m_b = \frac{\pi h^3}{12\mu \Re T_a \ln(r_b/r_e)} \left(p_e^2 - p_a^2\right) . \tag{3}$$

The formula for choked flow through a bearing having a supply pressure p_o and a throat at the perimeter of a square-edged supply hole of radius r_o is

$$m_c = 2\pi r_o h \rho^* a^* = 2\pi r_o h \rho_o \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{(\gamma-1)}} \left[\left(\frac{2}{\gamma+1}\right) \gamma \Re T_o\right]^{1/2} . \tag{4}$$

For ρ_o we can write

$$\rho_o = p_o/\Re T_o . \tag{5}$$

For nitrogen, the gas used in our experiments, we have**

$$\gamma = 1.404$$

$$\Re = 2.55 \times 10^5 (\text{in}^2/\text{sec}^2\ {}^\circ\text{R})$$

$$\mu = 2.56 \times 10^{-9} (T/528)^{1/2} \quad (\text{lb sec/in.}^2).$$

Assuming that the temperature in the gas film is a constant

$$T_o = T_a = T$$

we can combine Equations (3), (4) and (5) to obtain the following relation for nitrogen:

$$(m_b/m_c) = \frac{1.075 \times 10^6 p_o h \left[(p_e/p_o)^2 - (p_a/p_o)^2 \right]}{(r_o/h)\ T \ln [(r_b/r_o)(r_o/r_e)]} . \tag{6}$$

If Equation (1) is used to replace r_e/r_o in the above equation, the resulting expression for m_b/m_c has only one unknown, p_e/p_o. By setting

$$(m/m_c)_t = m_b/m_c , \tag{7}$$

as indicated in Step 3, we obtain a relation which can be solved for p_e/p_o. Equation (2) was used for m/m_c in Equation (7), and a computer program was written to obtain the values of p_e/p_o.

Now consider a circular thrust bearing having a square-edged supply hole of radius r_e, outer radius r_b, pressure p_e at $r = r_e$, and exit pressure p_a. (See Figure 1). Assuming a laminar pressure profile and following the theory of Reference 2, the theoretical load carrying capacity, W_t, can be shown to be

$$W_t = \pi r_e^{\,2}\, p_e\, e^{\frac{2}{A}} \sqrt{\frac{\pi A}{8}} \left[\operatorname{erf}\left(\sqrt{\frac{2}{A}}\right) - \operatorname{erf}\left(\frac{p_a}{p_e}\sqrt{\frac{2}{A}} \right) \right] , \tag{8}$$

**See Section 6 of Reference 1.

where

$$A = \frac{1 - (p_a/p_e)^2}{\ln\ (r_b/r_e)} \cdot \qquad (9)$$

Finally, recalling how r_e and p_e were defined*, we can obtain the value of load, W_C, that should correspond to the true value for the actual bearing geometry, as follows:

$$W_C = W_t + \pi r_o^2\ (p_o - p_a) - \pi r_e^2\ (p_e - p_a) \cdot \qquad (10)^{**}$$

2.3 Range of Application

Because the selection of Equations (1) and (2) was based on experimental data for a single bearing, the above analysis does not have general applicability. It will be possible to generalize the method after the program of measurements described in Reference (1) is completed. At present, the method can be applied only to circular thrust bearings having an axial, square-edged supply hole of 0.020-in. diameter. Arguments based on dimensional analysis can be set forth to show that the plots of r_e/r_o vs. p_o/p_e and m/m_c vs. p_e/p_o (Figures 2 and 3) should be independent of r_b/r_o. Therefore, there is no limitation on the bearing diameter, $d_b = 2r_b$. It must be remembered however that the smaller r_b, the greater will be the relative importance of entrance effects; and therefore the less accurate will be the results obtained by the above scheme.

---

*See the subtitle of Figure 1.

**An example of the computation of m_b and W_C is given in Appendix A.

3. DISCUSSION OF RESULTS

The design method described above was used to compute flow rates and loads for the conditions of the experimental tests, and the computed values were compared to the experimental values. The results are displayed in Figures 4 and 5. We see that the computed values of flow rate and load were mostly within 10% of the experimental values.

The above analysis was conducted primarily to determine whether any change in procedure should be made in the tests that remain to be run. The main change decided upon is that pressure profiles will be obtained with less detail than those reported in Reference 1. Since the pressure profiles are used mainly for computation of the load supported by the bearing, any detail which does not increase the accuracy of this computation is unnecessary. Without reducing the usefulness of the data, this will permit a reduction in time required per test.

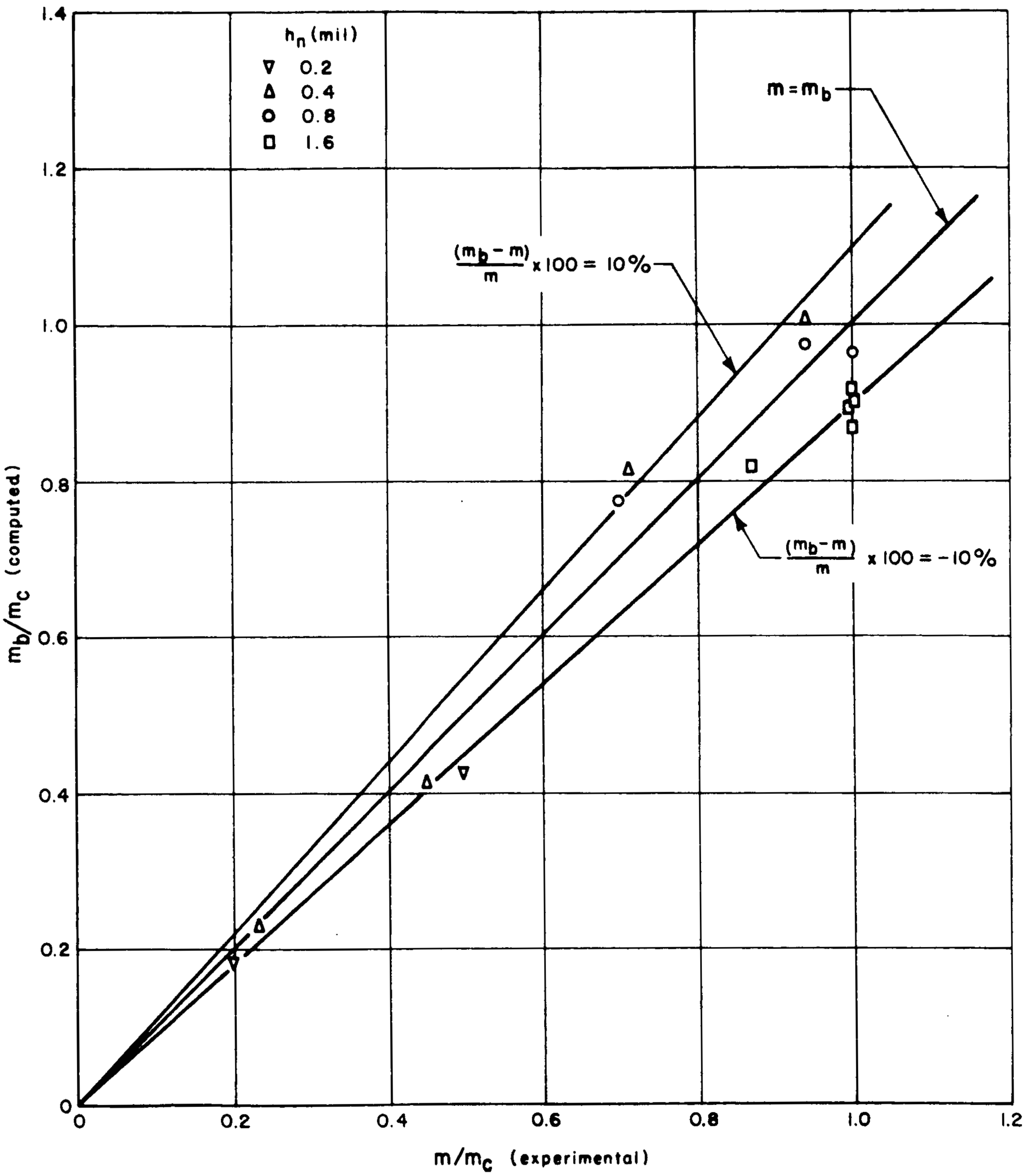

Fig. 4 - Comparison of Computed and Experimental Values of Flow Rate.

$r_o = 0.010$ in.

$r_b = 1.400$ in.

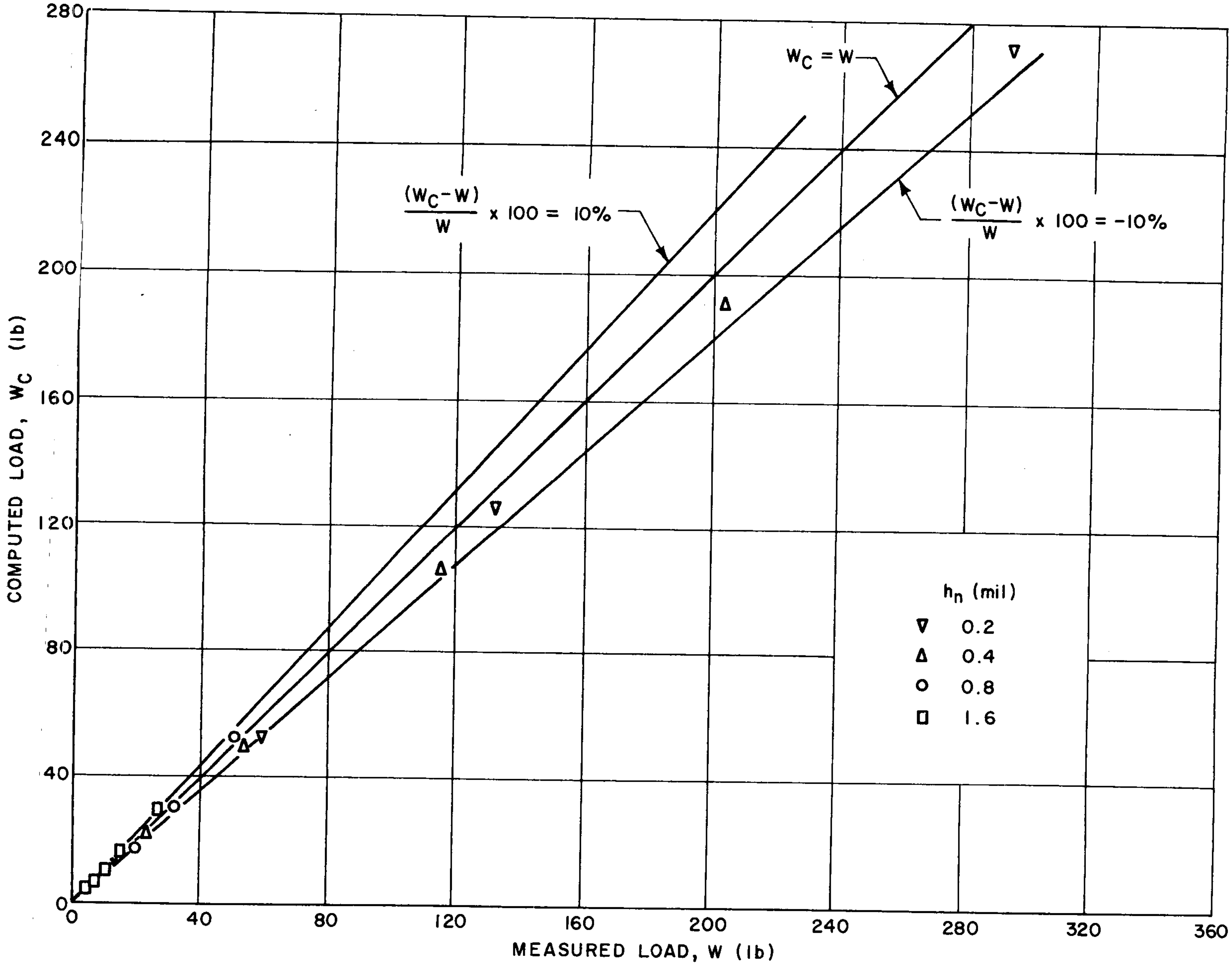

Fig. 5 - Comparison of Computed and Experimental Values of Load.

$r_o = 0.010$ in.
$r_b = 1.400$ in.

4. Conclusion

A method for taking account of entrance effects in bearing design has been described. When applied to conditions for which experimental data were available the computed values of flow rate and load were mostly within 10% of the experimental values. Applicability of the method is limited at present by the fact that the experimental data on which it is based were obtained with only one bearing geometry. This method can be generalized, however, after the test program is completed.

5. Plans

Completion of the experimental program described in Reference 1 has been delayed primarily by disruptions imposed when the Laboratories were moved to a new building. The apparatus has been reassembled and some improvements made. The bearing surfaces were refinished, and a new supply hole was drilled. While some tests have been conducted, reporting of the results will be postponed until the entire program is completed. It is anticipated that this will be accomplished in 1967.

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APPENDIX A

SAMPLE COMPUTATIONS

A-1. Example of Computations for r_e and p_e.

We shall consider Test 6 of Reference 1 as an example for illustrating the computation of the values of r_e/r_o and p_e/p_o plotted in Figure 2.

From page 27 and Table 7.2 of Reference 1, we have the following information

$$
\begin{aligned}
r_o &= 0.010 \text{ in.} \\
r_b &= 1.375 \text{ in.} \\
h &= h_c = 0.876 \text{ mil} \\
p_o &= 65 \text{ psia.} \\
p_a &= 14.80 \text{ psia} \\
S_{exp} &= \text{slope of straight-line portion of plot of } (p/p_a)^2 \text{ vs } \ln\,(r/r_b) = -\,1.837 \\
W &= \text{experimental load} = 31.42 \text{ lb.}
\end{aligned}
$$

From the slope of the straight-line portion of the plot of $(p/p_a)^2$ vs $\ln\,(r/r_b)$ and the fact that $p = p_a$ at $r = r_b$, it follows that

$$(p/p_a)^2 = 1 - 1.837 \ln\,(r/r_b). \qquad \text{(A-1)}$$

This expresses the relation between p and r over the laminar portion of the pressure profile. Using the relation at the bottom of Figure 1, we have

$$\int_{r_e}^{r_b} 2\pi p r dr - \pi(r_b^2 - r_e^2)\, p_a = 31.42 - \pi r_o^{\,2}\, (p_o - p_a). \qquad \text{(A-2)}$$

If we use Equation (A-1) to express p in terms of r in Equation (A-2), we obtain a relation in which everything is known except r_e. A computer program was prepared to solve Equation (A-2). For Test 6, the solution was $r_e/r_o = 1.611$. It follows that $r_e/r_b = 0.01172$; and substitution of this into Equation (A-1) yields $p_e/p_a = 3.028$, from which it follows that $p_e/p_o = 0.6915$. The point $p_o/p_e = 1.446$, $r_e/r_o = 1.611$ is one of those plotted in Figure 2.

A-2 Sample Design Computation.

We shall again use Test 6, Reference 1, as an example. Following the procedure outlined in Section 2.2, we choose

$$\gamma = 1.404$$
$$r_o = 0.010 \text{ in.}$$
$$r_b = 1.375 \text{ in.}$$
$$h = 0.876 \text{ mil}$$
$$T = 77°F = 537°R$$

Combining Equations (1), (2), (6) and (7), we have

$$\left(\frac{2}{\gamma+1}\right)^{-\frac{1}{(\gamma-1)}}\left(\frac{\gamma+1}{\gamma-1}\right)^{\frac{1}{2}}\left\{(p_e/p_o)^{\frac{2}{\gamma}}\left[1-(p_e/p_o)^{\frac{(\gamma-1)}{\gamma}}\right]\right\}^{\frac{1}{2}} = \frac{1.075 \times 10^6 p_o h\left[(p_e/p_o)^2-(p_a/p_o)^2\right]}{(r_o/h)\ T \ln\{(r_b/r_o)/[1.2(p_o/p_e)-0.2]\}}. \quad \text{(A-3)}$$

Using a computer to solve Equation (A-3), we obtained the solution $p_e/p_o = 0.6899$. Substition of this into Equation (1) yields $r_e/r_o = 0.6279$. Now, all the quantities in Equations (6), (8), (9), and (10) are known. Again using a computer, we obtained the following values

$$m_b/m_c = 0.9397$$

and

$$W_C = 30.65 \text{ lb.}$$

Since $m_c = 2.07 \times 10^{-7}$ lb sec/in.* we have

$$m_b = 1.945 \times 10^{-7} \text{ lb sec/in.}$$

These computed values of load and flow rate are within a few percent of the experimental values, which were*

$$m = 2.02 \times 10^{-7} \text{ lb sec/in.}$$

and

$$W = 31.42 \text{ lb.}$$

*See Table 7.2, Reference 1.

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An empirical method is presented for taking entrance effects into account in computing flow rates and load-carrying capacities of circular thrust bearings. Because of the limited data on which it is based, the method is applicable only to bearings having an 0.020-in. diameter supply hole; but it can be generalized when data for other supply hole diameters are obtained. When applied to the geometry for which experimental data were available, the procedure yielded values of flow rate and load falling within approximately 10 per cent of the experimental values.

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